Conceptual Communications System Designs in the 25.25–27.5 and 37.0–40.5 GHz Frequency Bands

Final Report
NASA/ASEE Summer Faculty Fellowship Program –1993
Johnson Space Center

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Date Submitted:	August 18, 1993
Contract Number:	NGT-44-001-800

ABSTRACT

Future space applications are likely to rely heavily on Ka-band frequencies (20-40 GHz) for communications traffic. Many space research activities are now conducted using S-band and X-band frequencies, which are becoming congested and require a degree of pre-coordination. In addition to providing relief from frequency congestion, Ka-band technologies offer potential size, weight and power savings when compared to lower frequency bands.

The use of the 37.0-37.5 and 40.0-40.5 GHz bands for future planetary missions were recently approved at the 1992 World Administrative Radio Conference (WARC-92). WARC-92 also allocated the band 25.25–27.5 GHz to the Intersatellite Service on a primary basis to accomodate Data Relay Satellite return link requirements. Intersatellite links are defined to be between artificial satellites and thus a communication link with the surface of a planetary body, such as the moon, and a relay satellite orbiting that body are not permitted in this frequency band.

This report provides information about preliminary communications system concepts for forward and return links for Earth-Mars, and Earth-Lunar using the 37.0-37.5 (return link) and 40.0-40.5 (forward link) GHz frequency bands. In this study we concentrate primarily on a conceptual system for communications between Earth and a single lunar surface terminal (LST), and between Earth and a single Mars surface terminal (MST). Due to large space losses, these links have the most stringent link requirements for an overall interplanetary system. The Earth ground station is assumed to be the Deep Space Network (DSN) using either 34 meter or 70 meter antennas.

We also develop preliminary communications concepts for a space-to-space system operating at near 26 GHz. Space-to-space applications can encompass a variety of operating conditions, and we consider several "typical" scenarios described in more detail later in this report. Among these scenarios are vehicle-to-vehicle communications, vehicle-to-geosyncronous satellite (GEO) communications, and GEO-to-GEO communications. Additional details about both the interplanetary and space-to-space communications systems are provided in an "expanded" final report which has been submitted to the Tracking and Communications Division (TCD) at the NASA Johnson Space Center.

Introduction

Future space applications are likely to rely heavily on Ka-band frequencies (20-40 GHz) for communications traffic. Many space research activities are now conducted using S-band and X-band frequencies, which are becoming congested and require a degree of pre-coordination. In addition to providing relief from frequency congestion, Ka-band technologies offer potential size, weight and power savings when compared to lower frequency bands.

The use of the 37.0-37.5 and 40.0-40.5 GHz bands for future planetary missions were recently approved at the 1992 World Administrative Radio Conference (WARC-92). WARC-92 also allocated the band 25.25–27.5 GHz to the Intersatellite Service on a primary basis to accomodate Data Relay Satellite return link requirements. Intersatellite links are defined to be between artificial satellites and thus a communication link with the surface of a planetary body, such as the moon, and a relay satellite orbiting that body are not permitted in this frequency band.

This report provides information about preliminary communications system concepts for forward and return links for Earth-Mars, and Earth-Lunar using the 37.0-37.5 (return link) and 40.0-40.5 (forward link) GHz frequency bands. Preliminary studies (see [1, 2, 3, 4]) have investigated the technical feasibility of millimeter wave frequencies for lunar and Mars exploration activities as proposed for the Space Exploration Initiative (SEI). The communications infrastructure proposed for the SEI program is illustrated in Figure 1. This figure depicts a complex communications scenario which has evolved to include elements such as point-to-point surface communications on both the moon and Mars, mobile communications using both manned and robot controlled rovers, message routing and relay satellites for nearly complete planetary coverage. Initial lunar and Mars missions are likely to be less complex with fewer links and components. In this study we concentrate primarily on a conceptual system for communications between Earth and a single lunar surface terminal (LST), and between Earth and a single Mars surface terminal (MST). Due to large space losses, these links have the most stringent link requirements for an overall interplanetary system. The Earth ground station is assumed to be the Deep Space Network (DSN) using either 34 meter or 70 meter antennas.

We also develop preliminary communications concepts for a space-to-space system operating at near 26 GHz. Figure 2 illustrates the types of applications envisioned for this frequency band. Space-to-space applications can encompass a variety of operating conditions, and we consider several "typical" scenarios described in more detail later in this report. Among these scenarios are vehicle-to-vehicle communications, vehicle-to-geosyncronous satellite (GEO) communications, and GEO-to-GEO communications.

Bit Rate Requirements

Space communications applications rely heavily on voice, command, scientific and visual information. Due to the high data rates involved, image/video requirements are usually a major factor in determining the bit rate requirements for various communications links. Link margin calculations (described later in this report) reveal that, for the near future, feasible return links from Mars will be in the 0.5–5 Mbps range. In fact, the 5 Mbps figure is derived by pushing the antenna, transmitter power, and receiver noise figure parameters to their outer reasonable limits, and thus initial return links from Mars are likely to operate at

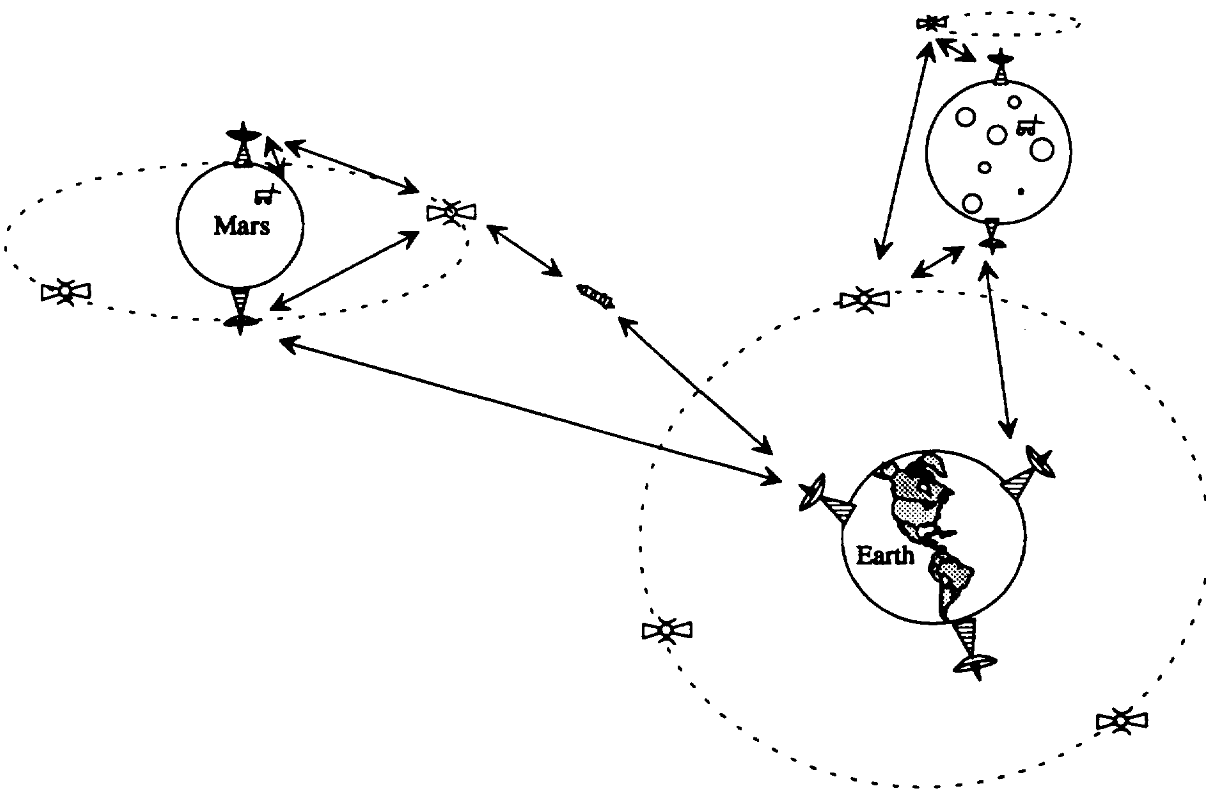

Figure 1: Telecommunications architecture for Mars and Lunar Explorations

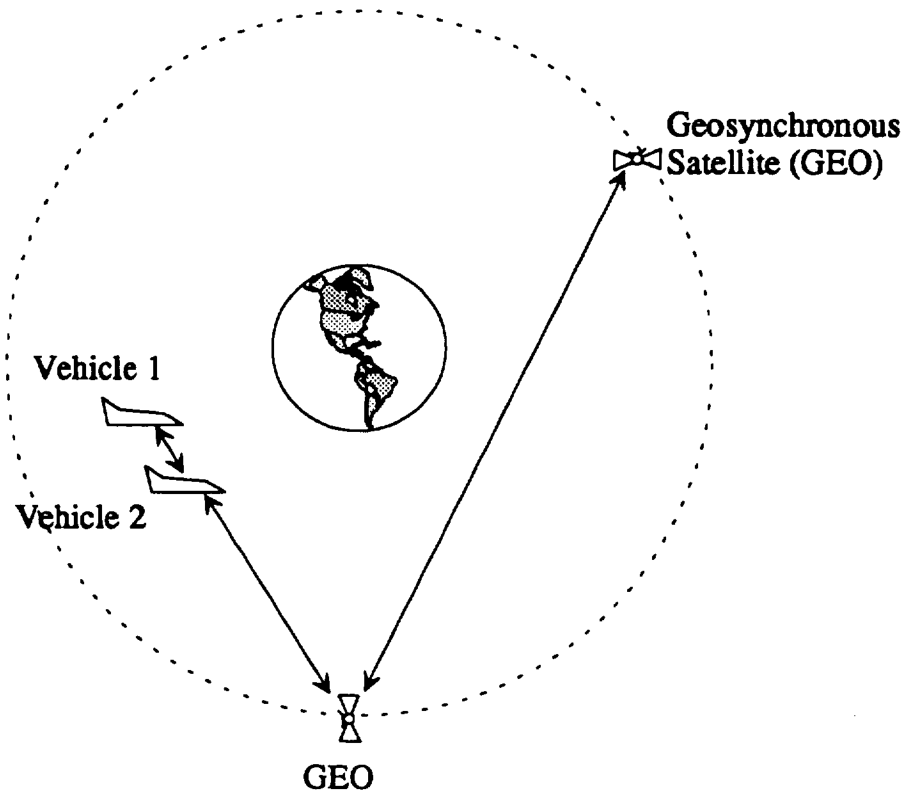

Figure 2: Space-to-Space Line Diagram

a lower maximum return rate, possibly on the order of 1 Mbps under clear sky conditions. However, the near-term development of Ka-band technology to support relatively large data rates for lunar and space-to-space applications appears to be feasible. The space loss for lunar applications is up to 60 dB less than that of Mars. Thus, lunar links are capable of supporting significantly higher data rates.

A combination of (at least) two approaches may be used to accommodate the desired video/image data requirements for space applications. These approaches become increasingly important when data rates are limited by space loss (communications to Mars) or by a high demand for communications resources. One approach is to employ high speed data buffering so that image signals that are not "real-time" critical can be stored and retransmitted at a lower rate. It should be noted that one-way transmission times between Mars and Earth are somewhere between roughly 4 minutes (minimum distance) and 22 minutes (maximum distance). This, of course, alters the nature of two-way communications and also presents difficulties for controlling automated systems from Earth. For comparison, one-way (direct) transmission time between the moon and Earth is less than 2 seconds. Data storage devices can also be used to ease coverage and fade requirements for interplanetary missions. The number of planetary surface terminals and/or orbiting satellites could be reduced by recording mission data during outage periods and then transmitting the recorded data when communications is restored. Another approach for reducing transmission bit rate and data buffering requirements is to employ data compression techniques.

Lossy compression schemes can offer significant data rate reductions and yet still maintain an acceptable level of perceptual quality.

The technology assessment in [5] has identified uncompressed image and video data rate requirements to be on the order of 0.5-1000 Mbps, depending on the application. Image/video data can be classified into several categories as indicated in the following sections.

High Rate Video

As described in [5], it is desirable for many space missions to support high quality full motion video similar to standard National Television Systems Committee (NTSC) video. Supporting this level of video quality will require an uncompressed data rate of approximately 100 Mbps. As video standards evolve from the NTSC standard to High Definition Television (HDTV), it is desirable that future planetary missions have the capability to support the higher quality standard. Although, uncompressed data rates for HDTV are in the 1 GHz range, commercial interests are a driving force behind developing compression techniques for broadcasting high quality digital HDTV over the existing commercial television bandwidth allocation of 6 MHz.

Edited High Rate Video

A reduction in the video frame rate results in a lower quality video signal which in turn lowers the required uncompressed transmission rate to the 10-20 Mbps range. Remote monitoring and video teleconferencing are examples of applications where edited high rate video may be appropriate. As a result of the reduced frame rate associated with edited video, motion within an image is likely to result in objectionable distortions. Compression techniques can reduce the required transmission rate by a factor of 10 or more.

Low Rate Video

Certain video applications applications, such as remote monitoring, may have relatively low bit rate requirements. For example, an 8-bit, 512 by 512 monochrome signal transmitted at one frame per second requires an uncompressed transmission rate of slightly more than 2 Mbps and a compressed data rate of 0.2 Mbps or less.

Science Imaging Data

Due to the wide variety in technical requirements, it is difficult to quantify the image data requirements for scientific research. Estimates for uncompressed data rates vary widely from a low of 0.5 Mbps to as high as several gigabits per second [5]. It is unlikely that initial return links from Mars will be able to support raw data rates beyond that of compressed high rate video. Therefore, in many instances tradeoffs between resolution, frame rate and distortion levels (for compressed data) must be made. With scientific data, care must be exercised in choosing data compression schemes since the perceptual models used to achieve large compression ratios may not preserve the desired information content of scientific data. Since lunar and some space-to-space applications can support higher data rates, in these cases it may be desirable to transmit scientific data using lossless compression formats.

Multimedia Data

Multimedia involves the integration of text, high and low resolution computer graphics, audio and video into a coordinated information display. Advances in this area promise to provide substantial improvements in mission operations. For example, mission construction and maintenance procedures can be "interactively" displayed to crew members using schematics, block diagrams and audio instructions. Furthermore, payload computers can be accessed and monitored by ground support facilities without flight crew intervention. A flight demonstration using Ku-band frequencies for transmitting 128 Kbps multimedia data to the space shuttle orbiter via commercial satellites has been proposed within the Tracking and Communications Division of NASA Johnson Space Center. Using compressed video and graphics it is possible to support multimedia with data rates as low as 128 Kbps. However, future multimedia applications, using higher resolution graphics and video, may require higher rates in the range of 0.5 to 5 Mbps.

Telerobotics Video

Telerobotics video relies on stereo images pairs to extrapolate the spatial information needed for autonomous or remote control. It is typically assumed that two high rate color video channels are needed for telerobotic video [5], resulting in an uncompressed transmission bit rate of roughly 200 Mbps. Some applications which require higher resolutions could push this figure into the Gbps range. Due to transmission delays high data rate telerobotics applications between Mars and Earth are impractical. Robotics applications will be forced to rely more heavily on autonomous control strategies thereby reducing the transmission bit rate requirements for telerobotic applications. Lunar communications links should be able to support the data rates required for advanced telerobotic applications. Furthermore, lunar transmission delays are sufficiently small so that lunar telerobotic applications are feasible.

Low Bit Rate Applications

Space missions must also support voice and command data applications. The data rate requirements for these uses are typically low when compared to the video/image case. Although water absorption in the atmosphere can lead to significant propagational losses at Ka-band, it appears that sufficient margin will exist to reliably maintain low bit rate applications for a Mars return link.

Link Margin Calculations

A link margin analysis is a valuable tool for determining a practical set of communications system parameters which are required to meet the system probability of error requirements. The link analysis consists of a "budget" which tabulates calculations regarding useful signal power and interfering noise power at the receiver. System gains and losses are totaled in terms of transmitter power, antenna gains, space loss, propagation losses, receiver noise figures, bit rate bandwidth and modulation/coding requirements. Link analyses of forward/return links for both a moon and a Mars link were performed using the proposed uplink frequency of 37 GHz and the proposed downlink frequency of 40 GHz. An example calculations for an interplanetary link is illustrated in Table 1. Several space-to-space scenarios operating near 26 GHz were also considered and are covered in the TCD report. The following sections give more detail regarding the calculations, models and assumptions used for the link margin results.

Transmitter Power

Size, weight and efficiency concerns give rise to transmitter power limitations for space based transmitters. This is especially true for space vehicles and satellites, however, planetary missions may have the payload capability to accommodate more powerful transmitters. Due to power requirements, the return link for interplanetary communications results in the most stringent link requirements. Table 1 indicates a 75 Watt transmitter at a Mars ground station. The technology for such a transmitter appears to be feasible for near-term development. In [1, 6, 7] the authors point out that Hughes has developed a 60 GHz, coupled-cavity Traveling Wave Tube (TWT) amplifier which has dual mode operation at 30 and 75 Watts, and 40% efficiency. In general, manufacturing tolerances are tighter for higher frequencies and thus a 75 Watt transmitter at 40 GHz appears to be a practical assumption.

For lower power applications, such as some space-to-space applications, solid state amplifiers offer size and reliability advantages over TWTs. It appears that Monolithic Microwave Integrated Circuits (MMIC) amplifiers in the 0.1 to 5 Watt range will be technically feasible for Ka-band applications [8].

Antenna Gain

For most of the link margin calculations it is assumed that the transmitting and receiving antennas are parabolic-shaped reflector antennas each with efficiency $\eta = 0.55$ and having an antenna gain G given by

$$G = 10\log((\frac{\pi D}{\lambda})^2\eta) \text{ dBi} \quad ,$$

where D is the antenna diameter (in meters) and λ denotes the operating wavelength (in meters). However, for certain space-to-space applications we assume the use of a low gain antennas in order to avoid size and pointing difficulties. In these situations we assume that $G = 3$ dBi. One of the more ambitious antenna assumptions used in this study involves employing a 70 meter DSN antenna at 40 GHz. Achieving an antenna efficiency near $\eta = 0.55$ requires a root-mean-square (rms) surface deviation of approximately $\lambda/20$ m [9]. At 40 GHz this translates to a 375 μm rms surface deviation. Future work should investigate the technical specifications regarding the planned DSN upgrade to Ka-band frequencies (which was briefly mentioned in [4]). It is certainly possible that surface irregularities, combined with gravitational and wind forces, may reduce the antenna gain values used in our link calculations.

Space Loss

For space communications systems, space loss is the single largest loss in the system. The space loss, L_s, of a system is a loss in the sense that not all of the radiated energy from the transmitter is focused on the intended receiver. The calculation for space loss is given by

$$L_s = -20\log(\frac{4\pi r}{\lambda})(dB) \quad ,$$

where r denotes the path distance (in meters).

The worst case path loss for the Mars link is calculated based on a maximum separation distance of 2.675 Astronomical Unit, (AU) (1 AU = 1.496×10^5 km). As the Earth and Mars orbit the sun, the distance between the two planets varies from 0.374 to 2.675 AU. In all of the link margin calculations the worst case path loss is used. Therefore, at minimum separation there is over 16 dB excess margin. The average separation distance between Earth and Mars results in approximately 5 dB of available margin that can be used to increase link availability during rain conditions or to enable higher data rates during clear sky conditions. The worst case path loss for a lunar link is based on a maximum separation distance of 406,700 km.

Atmospheric Losses

The clear sky atmospheric losses due to water vapor and oxygen absorption are calculated using the Global Model [10]. Since the DSN sites operate at an elevation angle in the range of 10^o to 70^o, a conservative elevation angle of 20^o is employed in the propagation loss calculations. Note that the rain margins required for achieving low outage probabilities ($p < 1\%$) can be prohibitively large since fades in excess of 20 dB are not rare. However, for a $p = 5\%$ outage figure, the Global Model predicts a propagation loss of approximately 4 dB at a 20^o elevation angle (at Canberra, Australia). Of the three DSN sites, Canberra, Australia has the most stringent rain margin requirements and thus the overall network availability will be somewhat greater than 95%. Figure 4 illustrates bit-rate performance as a function of rain fade for several power levels.

The composition of oxygen and water vapor on Mars (by percent volume or number of molecules) is 10^{-1} and less than 10^{-1}, respectively. This is compared to Earth's composition of 21% and less than 1% for these gases [11]. Absorption losses through the Martian atmosphere due to oxygen and water vapor are therefore assumed to be insignificant at Ka-band frequencies. However, it should be noted that the Martian atmosphere contains relatively high levels of carbon dioxide, nitrogen and argon (up to 50% by volume). The absorption effects of these gases are also neglected in the propagation loss calculations.

Receiver Noise Temperature

For applications where the receiver antenna points toward cold space, the receiver noise temperature can have a significant effect on system performance. For example, under clear sky conditions the antenna temperature, T_a, associated with the DSN network is relatively low. Data in [10] indicates an antenna temperature of $T_a = 20$ K at 40 GHz and elevation angle $\theta = 90^o$. However, for lower elevation angles the increase in antenna temperature can have a significant effect on link performance. For example, [10] indicates an antenna temperature of $T_a = 120K$ at 40 GHz and $\theta = 10^o$. For low noise receivers (Noise Figures in the range of 0.25 – 1 dB), this increase in antenna temperature can result in a performance loss of 2 – 4.5 dB. Rain conditions also have a significant effect on antenna temperature. As mentioned previously, Figure 4 shows the channel bit rate performance as a function of rain fade. Since the Earth ground stations employ low noise receivers it is important to account for the increased antenna temperature when analyzing rain fade margins. Equations from [10] which relate the attenuation along an earth-space path and the antenna temperature are incorporated into the calculations used for Figures 4. As the path attenuation becomes large the antenna temperature asymptotically approaches the mean absorption temperature of the attenuating medium (in this case, 275 K).

For lunar links, there is a significant increase in antenna temperature due to solar energy reflected from the moon's surface. For operations near 40 GHz, the antenna temperature is calculated based on a model given in [10] and is calculated to be $T_a = 350K$. Since space-to-space links could have the Earth in the field of view, an antenna temperature of $T_a = 290K$ is employed for these applications.

Receiver noise figures are assumed to be in the range of 0.25 to 2.0 dB for Earth ground stations. Commercial space systems have ground receivers with noise figures in the range of 0.5 to 2.0 dB [12]. Miller [4] mentions that the 0.25 dB (17 K) noise figure is a planned upgrade to the DSN network. Space based receivers typically have larger noise figures. As a point of reference, at Ka-Band frequencies the Advanced Communications Technology

Satellite has a 3.4 dB noise figure, which is considered low by today's standards for a space based receiver. Assuming modest technology advances in space receiver designs, the noise figure for space receivers is assumed to be in the 2.0–4.0 dB range.

Modulation and Coding

The use of TWT amplifiers for providing the larger power levels required for Mars and lunar applications also has a bearing on the choice of modulation and multiple access schemes. In general, it is desirable to use a constant envelope modulation scheme (such as Multiple Phase Shift Keying (MPSK)) when a TWT amplifier is employed. Furthermore, Frequency Division Multiple Access (FDMA) schemes require TWTs to be "backed off" from their optimal power output levels in order to reduce intermodulation noise. Thus, when TWT amplifiers are used, Time Division Multiple Access (TDMA) schemes are more desirable for providing multiple access.

The performance of a digital communications system can be improved by the use of coding. Coding involves the incorporation of redundancy (usually in the form of parity bits) in an effort to detect and correct errors that are induced by a noisy channel. Concatenated coding schemes are often used in space applications since they offer relatively high coding gains and also use interleaving to combat burst errors. A concatenated Reed-Solomon (RS) and convolution code (with Viterbi decoding) can provide coding gains in the 8.5–9.5 dB range for a bit error probability of $P_e = 10^{-8}$ [13]. Thus the required $\frac{E_b}{N_0}$ for BPSK is reduced from 15.2 dB (without coding) to 5.7 dB (with coding). The use of certain data compression schemes requires more stringent bit error probability requirements and hence we use $P_e = 10^{-8}$ instead of the often used $P_e = 10^{-5}$ value. However, the several of the space-to-space applications do not assume a concatenated scheme, but rather assume a convolution code and $P_e = 10^{-5}$. Since this approach requires $\frac{E_b}{N_0} = 9.6$ dB, and the coding gain is roughly 5 dB, the difference between the two approaches does not greatly effect the results of the link margin calculations. Of course, a concatenated scheme provides improved P_e performance at the expense of encoding/decoding complexity. Advances in integrated circuit technologies continue to push the data rates that can be achieved by various concatenated coding schemes to higher levels. We have assumed that coding gains of 9.5 dB can be achieved for the lunar data rates in the near future. Presently, a concatenated RS and short block code can achieve coding gains of up to 7.5 dB and can be implemented for high data rates [13]. A more detailed description of various concatenated coding schemes can be found in [14].

Note that traditional coding schemes achieve coding gain via bandwidth expansion. For example, a concatenated (255,223) RS code and a $\frac{1}{2}$ rate, constraint length 7 code mentioned in [1] requires that over 50% of the bits transmitted over the channel to be parity bits. In 1982, Gottfried Ungerboeck published a technique called Trellis-Coded Modulation (TCM) [15] that combines multilevel modulation and coding to achieve coding gain without the usual bandwidth expansion. As an extension of the summer's work, we are investigating the use of a concatenated RS and TCM scheme which achieves coding gain with only a modest degree of expansion, all of which is due to the RS code. Further work will continue in this area as we investigate the level of coding gain which can be achieved using this technique.

Pointing Loss

Pointing loss is a potentially major issue for implementing an interplanetary communications system. For this study we use a "placeholder" value of 0.5 dB to represent pointing loss. Using an approximation given in [16] we have that the 3 dB beamwidth, θ (which is in degrees) is given by

$$\theta = \frac{75\lambda}{D} \quad .$$

At 40 GHz, $\theta = 0.008^0$ for a 70 m DSN antenna, and $\theta = 0.056^0$ for a 10 m MST antenna. Thus, the beam spot size at the MST is approximately $5d_m$, where d_m denotes the diameter of Mars. The beam spot size at the DSN is roughly $18d_e$, where d_e denotes the diameter of the Earth. A lunar link with a 10 m Earth GS and a 2 m LST will result in beam spot sizes of $1/10d_m$ and $1/10d_e$, respectively, where d_m denotes the diameter of the moon. Further work in this area is needed to more accurately quantify pointing losses for interplanetary applications.

Polarization Loss

In this study a placeholder value of 1 dB is used to represent polarization loss. The underlying assumption is that both the transmitting and receiving antennas employ circular polarization. The 1 dB placeholder value is based on assumptions used by [1] and [4].

Implementation Loss

Given the lack of hardware development at Ka-band frequencies, it is not possible to precisely determine all of the link parameters. For this reason a placeholder value of 2 dB is used to represent the expected losses due to the practical implementation of each communications system. Note also that the link calculations in this report are designed to achieve a 3 dB circuit margin.

Discussion and Conclusions

As mentioned previously, Tables 1 provides a "typical" link margin calculation for an interplanetary communications link. Note that the Earth to Mars link requires significantly more power due to the fact that space based receivers have significantly higher noise temperatures. Due to the difference in space loss, a lunar link can support significantly higher data rates when compared to the Mars application.

Figures 3 and 4 illustrate various tradeoffs between channel bit rate, transmitter power, rain fade margins and transmitter/receiver antenna size. Example nominal link parameter values and circuit margin equations are given in Table 1. Unless otherwise stated within the figure or the figure caption, the graphs shown in Figures 3 and 4 are based on the default parameters found in the appropriate tables mentioned previously. Both of the figures are calculated assuming a 3 dB circuit margin. Figures 3 illustrates a trade between transmitter antenna diameter and transmitter power for the Mars return link. Figure 4 illustrates the degrading effect on system performance that can be expected due to rain fades. It is desirable for the interplanetary communications systems to have the capability to accommodate several data rates. During fading conditions communications can be maintained by switching to a lower data rate. Furthermore, the space loss variability for a Mars mission is significant and can be exploited to provide rain margin and/or increased data rates.

Table 1: Mars to DSN Link Margin Calculations (37 GHz)

xmt power, dBw	18.8		75	Watts
circuit loss, dB	-2.0	estimate		
antenna gain, dBi	63.1	dish size	5	m
		frequency	37	GHz
		efficiency	0.55	
EIRP, dBw	79.9			
			2.675	AU
space loss, dB	-295.9	range	400180000	km
		freqency	37	GHz
polarization loss, dB	-1.0	estimate		
rcv antenna gain, dBi	86.1	dish size	70	m
		efficiency	0.55	
propagation loss, dB	-1.4	Global Model		
pointing loss, dB	-.5	estimate		
Total Received Power (TRP), dBW	-132.8			
System Noise Temperature	19.2	Antenna Temp	32	K
		Noise Figure	0.5	dB
		rcv circuit loss	0.1	dB
Receive G/T, dB/K	66.9			
Boltzman's constant, dBW/K/Hz	-228.6		1.38E-23	W/K/Hz
noise spectral density	-209.4	System Noise Temp+Boltzmann's constant		
TRP/NSD, dB	76.6			
bit rate bandwidth, dBHz	66.0		4	Mbps
implementation loss, dB	-2.0	estimate		
modulation loss, dB	.0			
coding gain	9.5	concatenated RS-convolutional		
Received Eb/N0	18.1	TRP/NSD-bandwidth+imp. loss+mod loss+coding gain		
Required Eb/N0	15.2	BPSK, BER=10e-8		
Link Margin	2.9	Received Eb/N0-Required Eb/N0		

Table 1: Mars to DSN Link Margin Calculations (37 GHz)

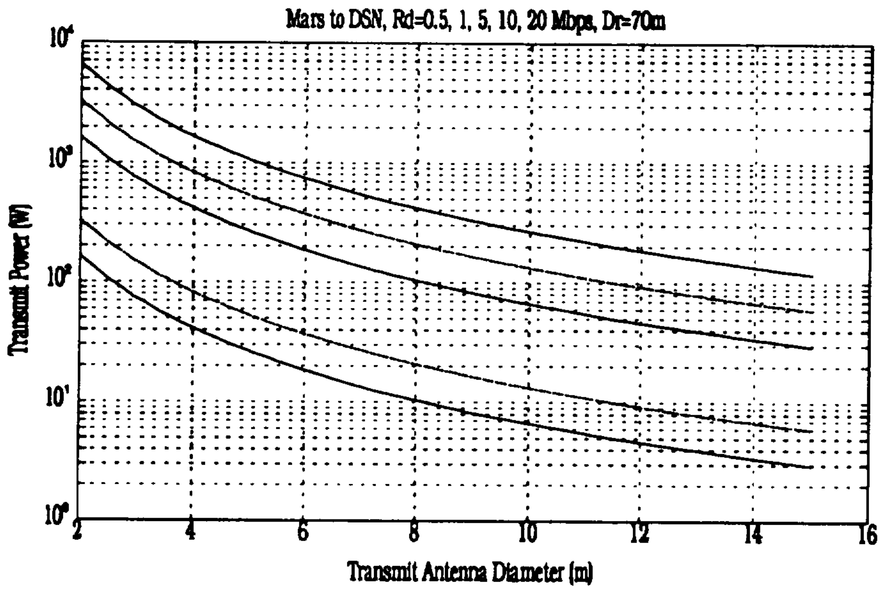

Figure 3: Mars transmitter power (W) versus transmit antenna diameter for channel bit-rates of 0.5, 1, 5, 10 and 20 Mbps and a 70 m receive antenna. Link parameters not specifically listed above are shown in Table 1. The curves are in descending order by bit-rate with the 20 Mbps curve on top and the 0.5 Mbps curve on the bottom.

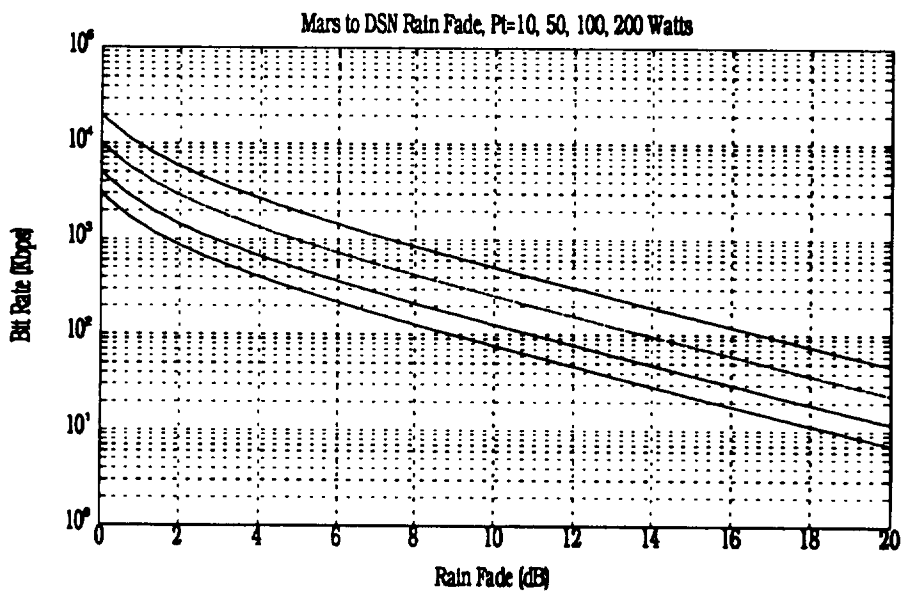

Figure 4: Bit-Rate (Kpbs) as a function of rain fade (dB), for Mars transmitter power values 10, 50, 100 and 200 watts. Link parameters not specifically listed above are shown in Table 1. The curves are in ascending order by power level with the 10 watt curve on bottom and the 200 watt curve on top.

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